FINAL REPORT

RESEARCH STUDY OF THE UTILIZATION OF BIOLECTRIC POTENTIALS

by

J. J. Konikoff

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

31 October 1964

Contract NAS-2 1420

NASA Ames Research Center

Moffett Field, California

General Electric Company

Space Sciences Laboratory

Missile and Space Division

P.O. Box 8555, Philadelphia, Penna. 19101

CONTENTS

FIGURES

I. INTRODUCTION

It has long been known that electrical energy is generated within the animal body. However, because of the relatively low level of power produced no practical utilization of these bioelectric potentials has been contemplated other than for diagnostic purposes, i.e. electroencephalograms, electrocardiograms, electromyograms.

Recent advances in micromimiturized electronic circuity have resulted in the application of transistors and tunnel diodes with the attendant important reduction in power requirements. Hence, the investigation of the bioelectric potentials as a possible power source for this class of electronic devices has become much more promising.

In 1962 a study of the utilization of the bioelectric potentials, as derived from anesthetized rats, was undertaken at the Space Sciences Labortory of the General Electric Company. This work resulted from an investigation aimed at the elucidation of the emf derived from the activity of microorganisms.

In May, 1963, the NASA Ames Research Center awarded the General Electric Company Contract No. NAS-1420 to investigate the utilization of bioelectric potentials with particular emphasis upon the following tasks:[1]

a) Electrode Material

b) Anatomical Sites

This document is the final report of the research conducted under this contract.

II. PREVIOUS WORK

Pinneo and Kesselman[2] have reported that they have been able to power an FM transmitter by inserting two steel electrodes into the brain of a cat. The transmitter has an energy input requirement of 0.5 microamps at 40 milliwatts. Long[3] presented an intensive study of these biological energy sources: biological potentials and chemical gradients, blood pressure and flow, muscular activity and motion, and concluded that the last named might have a more immediate application. Konikoff and Reynolds[4] extended their studies of biochemical fuel cells to the whole animal by analogous thinking. By considering the body as a container of electrolytes, numerous semipermeable membranes, and different tissues which metabolize differently, thus permitting a chemical gradient to exist, it becomes necessary only to add a catalytic agent and an electron collector (electrode) to construct a "living fuel cell". To test this thesis, experiments were conducted by measuring the electrical output when two metallic electrodes were placed in the same or different anatomical loci of anesthetized rats.

Results of these preliminary experiments indicated that an appreciable emf was produced. Values ranging up to 240 mv at 480 μa (115 μw) were measured over short periods of time, using a stainless steel/platinum-platinum black electrode system.[5] The platinum-platinum black (PPb) electrode was located within the abdominal cavity and the stainless steel (ss) electrode was inserted beneath the skin. Under an impedance of 10,000 ohms resulting from a specially designed oscillator, a voltage of 0.35 to 0.40 V was obtained. A receiver equipped with a loudspeaker picked up the signal generated by the oscillator at 500 kc and broadcast a loud, clear sound when located at a distance of approximately 25 feet from the rat and oscillator. Figure I illustrates the rat/oscillator hook-up and shows the transmitted sine wave as presented on the oscilloscope.

The output from the bioelectric potential and applied as described above is attributed to the natural differences in oxidation-reduction potentials which exist in different parts of the anatomy and are enhanced by the use of one electrode containing Pt-black which is a well-known catalytic material.

III. EXPERIMENTAL STUDIES

a. Methods

1. Initial electrode studies were conducted on rats weighing approximately 200 grams. The animals were anesthetized with Nembutal prior to any surgical procedures. The initial anatomical site chosen for the insertion was the abdominal region of the body. The choice was made primarily because of the relatively large space available for electrode insertion. Preliminary work was carried on with alligator clip electrodes which were attached to the skin and the brachial region and another electrode of the same physical configuration being inserted into the coelom through a small hole in the abdominal wall. The leads were connected to a variable resistance that led to a sensitive instrument voltmeter. The current was calculated by varifying the resistance and observing the change in voltage. A polarization curve was prepared by plotting the voltage against the current. In time, the indicating voltmeter was replaced by a Varian recorder. A Precision Decade box, 0-99,900 μ capacity was used to impress the known resistances on the circuit. In this manner, greater accuracy was obtained and the long-term effect could be visually obtained.

The experiments continued using other materials. Approximately 40 combinations have been studies. Figure 2 shows a typical polarization curve and Figure 3 illustrates the recording of the voltage during an 8-hour test.

2. A narrow category of materials was selected for investigation. These electrode candidates were chosen because of their biological inertness. At the same time, it became necessary to select one or two materials as a "standard" inasmuch as an evaluation of anatomical loci was also of interest. To this end a high speed steel (HSS) / platinum-platinum black (PPb) electrode system was selected based upon the apparent maximum output achieved with this combination.

3. Organs such as liver, brain, and stomach were not tested because they are not considered ideal for long-term implantation of metallic electrodes. Such sites as intestine, rectum, abdominal cavity, bone, muscle, and the subcutaneous region were tested in pairs. For example, the PPb was placed in the abdominal cavity and the HSS subcutaneously.

4. To determine the interaction between the implanted electrode and the host, long-term implant studies were conducted. Experiments were made with both passive and active electrode systems. The passive studies entailed the surgical implantation of representative electrode material. The active electrode resulting from an interaction between the material and the interstitial fluids was additive to the reaction occuring at the electrode as a result of the current drain.

5. Since the ultimate use of the bioelectric potentials is to power electronic devices, a concurrent study was undertaken in which electronic gadgetry in the form of transmitters and sensors (pickup) was designed and operated by implanted electrode pairs.

b. Results

1. Electrode- Electrical Characteristics

Table I presents the results of the material screening investigation as measured on an anesthetized rat. The compositions of those materials which are under trade names are shown on Table II. The experiments were standardized by two means. First, it became apparent early in the study that the abdominal region was a fortuitous choice because when coupled with a subcutaneous site, the electrode pair produced the greatest difference in potential. Also, the abdominal cavity is large enough to accommodate electrodes. The second related to the measurement of the voltage under load. It was established as standard that comparison values were to be taken at a resistance of 10,000 Ω. Thus, computations of power output could be compared with one another directly.

Several measurements shown on Table I are not the result of a 10 K Ω loading. This is because the values at the standard resistance were insignficant.

Examination of the results indicate that the greatest output (with no tissue interaction) is derived from a high-speed steel-platinum/platinum-black electrode combination. At a 10KΩ resistance, an output of 29.2 μ w results at a voltage of 0.54v.

Manganese steel produced a higher output but caused adverse tissue reaction in the animal. The amalgamated materials, i.e. Ag, Hg, Pb, when coupled with PPb also resulted in substantial outputs (approximately 50-75 percent of that obtained with the HHS). However, great difficulty was experienced in the preparation of the amalgam, its formation into an electrode, and the attachment of a lead wire. Consequently, this class of materials was also eliminated.

In the following sections of this report, it will be seen that there is an inconsistency in the output measurements using the HSS and PPb electrode combination. This lead to a study to determine the cause and recommend correction. Since great care had always been exercised insofar as duplicating the physical dimensions and characteristics of the electrodes, this cause was eliminated. The HSS electrode was also eliminated from consideration because of its obvious stability. Therefore, the PPb containing a thin film of platinum black sandwiched between two screens of platinum gauze was subjected to examination. Preliminary results indicated that variations in the open circuit voltage resulted when different PPb electrodes were coupled with one HSS electrode.

Visual examination of the PPb indicated a variation in cleanliness and structural integrity of the platinum black. In order that a realistic evaluation be made to determine whether variations in output resulted from electrode material or from unclean or chemically spent electrodes, and experiment was conducted in which several different techniques were used for cleaning the PPb electrode, in the following manner: A new PPb electrode was prepared and implanted in an animal (rat) and the output was measured against a HSS electrode implanted subcutaneously. This value was recorded and used as a standard. Following this, four more PPb electrodes were prepared (from materials already used), all of the same physical configuration and surface area, and then each of these electrodes was individually washed in 1 N solution of hydrochloric acid for periods of time varying from one half hour to eight days. Following their immersion in hydrochloric acid, each of these was washed again in distilled water, then implanted, and the outputs were essentially the same as the output recorded with the new PPb. Therefore, it was concluded that the variation in OCV resulted from improperly cleaned PPb electrodes. This cleaning procedure, i.e. maintain, store, and cleanse

PPb electrodes in 1 N solution of HCl prior to use, remove from the acid bath and wash in distilled water, was adhered to for the remainder of the program.

It is interesting to note that the variation in output resulting from unclean PPb electrodes is only apparent when the electrode is removed from a test animal and then reinstalled without adequate cleaning. No variations occur after implantation and the normal post operative recovery period. Consequently, it is important to understand that the variations are the result of experimental use, frequent short-term implantations resulting in the formation of a bacterial surface contamination when the electrode is removed and stored in the air or water, and not because of a degradation of the catalytic activity of the platinum black.

Figure 4 illustrates several electrodes and gives an indication of their relative size.

2. Electrodes- Anatomical Loci

As described earlier, it became readily apparent that the maximum output was obtainable when the PPb electrode was located in the abdominal cavity dorsad to the peritoneal membrane and HSS situated subcutaneously but physically adjacent to the abdominal incision. This was done to decrease the lead wire lengths as well as for surgical neatness. Early experiments indicated the importance of placing the PPb abdominally. This was demonstrated with a tantalum/PPb electrode system. When the Ta was abdominal the power output was 1.7 μ w whereas when the Ta was subcutaneous (PPb abdominal) the output measured 11.6 μ w. This increased output was consistently obtained.

Placing the dissimilar electrodes in the same anatomical locus resulted in reasonable outputs although the measured values were about one-half that obtained by placing the electrodes in different loci. Table IIIa shows the data when the various materials are located subcutaneously while Table IIIb presents the results when both electrodes are implanted abdominally.

Continuing the explorations of the effect of the bioelectric potential as a function of anatomic loci, experiments were conducted on a rabbit in which a bone plate made of stainless steel was implanted under the biceps femoris. The lead from the electrode was sutured to the surface of that muscle just under the skin and the skin was closed with silk sutures. The electrode was so placed that it was in contact with the muscle and was at the same time insulated from the bone adjacent to that muscle. The other electrode (PPb) was located in the coelom. It was found that the output under these conditions was extremely low, the open circuit voltage being approximately 0.17V whereas the voltage under a 10K Ω resistance dropped to 0.02. A test with a high-speed steel electrode similarly placed yielded somewhat better values which still were not the same as normally achieved when the high-speed steel is located subcutaneously. The values under these test conditions indicated an open circuit voltage of 0.42 and a voltage of .24 under a 10K Ω resistance. The second electrode for these tests was also PPb located in the coelum.

Another location was investigated, the back muscles.

a) Platinum-platinum/black and high-speed steel electrodes were implanted one on each side of the superficial fascia. HSS electrode was implanted beneath the fascia and dorsad to the muscle of the back. These first implants were performed on a rat with the following results:

@10K Ω

OCV	V	μa	μw
.72	.38	38.0	14.44
.74	.35	35.0	12.25

b) Same experiment as above except positions of electrodes were reversed.

@10K Ω

OCV	V	μa	μw
.73	.34	34.0	11.56

c) PPb electrode was sutured to the diaphragm. High-speed steel electrode was placed subcutaneously ventrad to the rectus sheath and slightly to the right of the linea alba. This experiment was performed on a rabbit.

@10K Ω

OCV	V	μa	μw
.73	.36	36.0	12.96

The output never stabilized, falling off to about 0.2V after several hours. The experiment was then terlminated.

d) A circuit was assembled consisting of PPb and HSS electrode connected to a 10KΩ resistance. This circuit was implanted in a rabbit dorsad from the latissimus dorsi, posterior to the last rib and slightly to the left vertebrae. The HSS was located between the superficial fascia and the dermis, the PPb between the superficial fascia and the latissimus dorsi. The leads were brought through the skin near the vertebrae. Post-operative voltage was 0.61V which at a resistance of 10KΩ yields 61.0 μa, resulting in a power output of 37.2 μw.

Figure 5 and 6 illustrate the animal, electrode leads, and recorder shortly after the surgical procedure.

After a post-operative period of eight days, voltage measurements taken at 10KΩ resistance indicate a value of 0.01 V. The voltage drop could have been due to several reasons:

1) Circuit failure

2) Failure of the facia and surrounding area to properly recover following surgery.

3) Longer equilibrium time is required.

To determine cause, a second rabbit was operated on and a circuit implanted as before. After ten days, electrical measurements again indicated a severe drop in voltage. Histological examination of the excised tissues following sacrificing of the rabbit indicated that the supply of blood to the affected region was severly impaired by both the surgery and the electrode/resistance assembly. Hence, although the rabbit appeared normally healthy, the affected area was slowly decaying.

As the result of the investigations described above concerning the bioelectric output obtainable from different anatomical loci, it is concluded that the maximum output occurs when the abdominal cavity houses the PPb and the HHS is slipped under the skin adjacent to the incision.

3. Effect of Electrode Size on Electric Output.

In general it may be stated that the total output is a function of the active surface area of the electrode. As a consequence, an investigation was made into the effect of electrode size on output. Intially, rats were used, eventually being supplanted by rabbits.

Studies were conducted using the HSS and PPb combination as these materials resulted in the greatest output. It was found that increasing the size of the subcutaneous electrode (the HSS) and maintaining the surface area of the PPb at its original value had little or no effect on the output. However, reversing this, maintaining the HSS electrode at its original value, and increasing the size of the PPb electrode, resulted in an increase in output. Increasing the surface area of both resulted in approximately the same increase as increasing the surface of the PPb or abdominal electrode only. The following Table, IVa, illustrates these data using new PPb material.

TABLE IVa

Initial Results of Electrode Size Study

Surface Area, Cm^2		Power		Comments
PPb Abdominal cavity) (+)	HSS (Subcutaneous) (-)	V at 10K	μw	
1.5	2.0	.54	29.16	Standard size
8.36	2.0	.64	40.96	--
8.36	4.0	.63	39.69	--

Continuing the study resulted in conformation of these data. Several different PPb electrodes were used, some quite old and, physically, in poor condition due to handling, resulting in inconsistent results. Table IV b below presents the data obtained from the older PPb material.

TABLE IVb

Output Vs. Electrode Area

Surface Area, Cm^2		Approx. area Multiple		Volts @	μa @	Power μwatts @
PPb	HSS	PPb/HSS	OCV	10KΩ	10K Ω	10KΩ
1.5 (std)	2.0(std)	1x/1x	0.76	0.27	27.0	7.3
12.0	2.0	8x/1x	0.70	0.63	63.0	39.7
16.8*	2.0	11.2x/1x		0.49	49.0	24.0
20.5	2.0	14x/1x	0.75	0.68	68.0	46.2
1.5	14.0	1x/7x	0.75	0.26	26	6.8

*Multi-wafer electrode assembly

From these reading it was established that the effect of electrode size on output is an important one. A polarization study was made using a rabbit wherin the voltage resulting from a given load (resistance) impressed on the circuit was determined. Three values of resistance were selected, 10,000Ω, 5000Ω, and 1000Ω. Prior to the tests, new electrodes were prepared because of the poor physical condition of the original platinum black cayalyst. The results are shown on Table V. and figure 7, which plots the results at a loading of 10KΩ.

TABLE V

Polarization Data

Electrode Surface Area vs. Output*

Pt-Pt- Bl Surface Area Cm^2	Voltage at			Amps at			Watts (Power) at		
	10KΩ	5KΩ	1KΩ	10 KΩ	5 KΩ	1 KΩ	10 KΩ	5 KΩ	1 KΩ
1.5 (1x)	0.46	0.19	0.06	46	38	60	21.2	7.2	3.6
12.0 (8x)	0.70	0.65	0.46	70	130	460	49	84	211
20.5 (14x)	0.76	0.725	0.555	76	145	555	57.8	103	308

*Against a 2.0 cm^2 high-speed steel electrode implanted beneath the dermis and dorsad to the fascia; the PPb is located between the fascia and the external oblique.

These results indicate that outputs substantially higher than previously obtained may be achieved by the simple expediency of increasing the PPb electrode surface area. A value of over 300 μ watts results from an approximately 2-inch diameter electrode. The method of increasing the electrode area is not restricted to only the physical enlargement of a single PPB electrode. The increased surface area may be obtained by assembling a number of wafers. The output value listed in Table IVb at the 11.2 times increase in PPb area results from an electrode assembly using four rectangular wafers each being approximately 1 cm x 2 cm, and spaced about 2 mm apart by a 1 x 2 cm sponge. Figure 8 is a sketch illustrating this technique. Examination of the results of this geometry indicates that the output is not in line with the results obtained from single enlarged PPb electrode. The probable explanation is because of the narrow spacing between wafers. This apparently resulted in the unavailability of the total surface area to contribute to the reaction.

4. Electrode Interaction with Host Animal

a. Passive

Electrodes of stainless steel (type 310), chromium, Ni foam, high-speed steel, and manganese steel were implanted in the subcutaneous regions of several rats. A PPb electrode was implanted in the intraperitoneal cavity of each animal. A silicon rubber (RTV) disc was also implanted in the subcutaneous region because this substance is used for potting the electrical circuitry. These metallic materials were selected because of their performance in power production.

These electrodes were not connected to an electrical circuit. The main purpose of the experiment was to determine the effect of the material on the adjacent tissue (foreign body reactions, chemical reactions).

After 80 days, the rats were sacrificed and the immediate implant area was grossly examined for tissue abnormalities. In all cases, the electrodes were covered with healthy connective tissue. This reaction is to be expected. No gross tissue anomalies were observed.

The metallic electrodes (with the following exceptions) showed no surface corrosion. All maintained their initial clean, bright appearance. Manganese steel and Ni-foam each indicated slight surface discoloration, indicative of a reaction occuring at the surface. As a result, these materials are excluded form further consideration. The chromium had lost its shine, altho no overt reaction could be detected. To further check this, PPb and chromium electrode couple was implanted in the abdominal cavity and subcutaneously, respectively, of a rabbit for additional verification. After 160 days the animal was sacrificed and the electrodes removed. The PPb which was sutured to the peritoneal membrane was examined and found to be completely encapsulated in mesentery which contained a good blood supply. (See Figure 9) The chromium electrode was removed with all surrounding tissue including some dermis. This electrode was also encapulated in what appeared to be a healthy tissue except for some blue-green discoloration. The electrode was excised, and it was found that the chromium was badly oxidized and flaky. (See Figure 10) The discolored area in the surrounding tissue was due to the absorption of the chromate. Based on this reaction, chromium has also been excluded.

b. Active

In order that a realistic test be accomplished in which a valid conclusion could be evolved as to the interaction of the electrode system and the animals, a simple circuit was assembled and used for test purposes during the long-term implants studies. This circuit consisted of two electrodes with a 10 KΩ resistance added so that a constant power drain occurred. A pair of leads, initially platinum wire, then braided multi-stranded stainless steel cable (.018", 7 x 3), nylon coated to 0.032" diameter was attached to the circuit and brought out through the skin so that electrical measurements (voltage readings) could be made. Figure 11 is a photograph of such a circuit containing the 10 KΩ resistance, with chromium/PPb electrodes potted in silicone rubber (RTV). Figure 12 illustrates a HSS/PPb circuit unpotted.

These experiments were conducted in rabbits and dogs. Initially, four implants were made in as many rabbits. The materials used were PPb-abdominal cavity, and HSS or chromium-subcutaneous. The circuits were constructed as described above, and voltage readings were measured at two-day intervals. These data are plotted on Figures 13 and 14. The differences between the same material combinations are the results of PPb variations, and gave rise to the concern for standardizing this electrode material. Nevertheless, the data suggest that sufficient power is produced to power a 10KΩ impedance transmitter for the number of days shown.

The experiments were terminated in every case because of broken leads.

This type of experiment was extended to two dogs. PPb and HSS electrodes were used, each having a 10KΩ resistor soldered across them in parallel to form a circuit. These circuits were potted in silicone rubber prior to implantation. In the one case the PPb was located in the abdominal cavity and the HSS subcutaneously (Test 1). In the other animal the HSS electrode was separated from the PPb electrode by the peritoneal membrane (Test 2). These tests were continued for a total of 62 days during which the output has been measured daily (Test 1). Test 2 had a total implant time of 62 days and daily measurements were made for 37 days. Hence, a realistic appraisal may be made of the effect of the implant and also the effect of the animal on the output of the implant. The animals were permitted the relative freedom of their respective cages after the surgery is performed.

Figures 15 and 16, respectively, plot the voltage readings over the test periods which were concluded because of a) an infection found at the point of incision and b) a broken lead.

The power output for these tests averaged about 9.6 μw for Test 1 and 13.7 μw for Test 2. The electrodes were examined after removal from the animals and showed only the usual fibrous coating which is expected whenever a foreign body is implanted. The coating did not appear to greatly retard the production of electric power.

Comparison of the output curves shown on Figures 15 and 16 indicates that a more uniform output was derived from the animal that had the electrode positioned on either side of the peritoneal membrane. For this implant the resistor was anchored to the rectus abdominous in the subcutaneous region and the leads were threaded through a small stab wound, lateral to the main incision. These were held in place with a purse-string suture.

Removable rubber caps were used to cover the bare ends of the leads. The electrodes were located as shown in Figure 17. As can be seen, the subcutanous HSS electrode is now located beneath the muscle layer immediately over the peritoneal membrane.

Based upon these results, it appears justified in concluding that the fixing of the electrodes by means of sutures is also important in obtaining a more or less steady output and reducing possible animal discomfiture.

One final long-term experiment was conducted using a rabbit. The purpose of this test was two-fold:

a) Check constancy of output as a result of suturing electrodes in place

b) Check output gain as a function of electrode (PPb) area increase.

To this end, a four-wafer PPb electrode as described previously was made (See Figure 8) and surgically tied to the peritoneal sheath within the peritoneal cavity. The HSS electrode was positioned between the obliquus externus and obliquus internus. A 10 KΩ resistance was connected in parallel to the electrode system, thus causing a constant power drain. The leads were brought out at the nape of the neck after being threaded through a subcutaneous tunnel. A voltage reading was taken approximately every three days. This experiment was continued for 128 days and terminated by sacrificing the animal at the convenience of the experimenter. During the trial period the rabbit was permitted the relative freedom of his cage and appeared to be completely normal following the usual post-operative recovery period (about 2 days). Figure 18 presents the measured values of volts over the trial period. As can be seen, after about 15 days, the output became quite steady and continued in this manner throughout the remainder of the test. Actual voltage fluctuations were about 0.01 volts, varying from 0.49 to 0.50. The power output under these operating conditions (.49V @ 10K Ω resistance) is computed to be 24 μ watts at .49 μ amps.

Upon termination of this experiment (because the contract time was over) the electrode materials were removed and examined for surface discoloration or other anomolies which might indicate possible interaction with the host animal. No signs of such activity were noted. Gross examination of the animal tissue in the vicinity of the electrode loci also resulted in negative findings.

IV. APPLICATION STUDIES

a) Signal Transmission

Data obtained form the electrode material studies shown on Table I were used to draw specifications for an oscillator to be constructed and have the capability of operating when drawing power only from a rat. The device was designed to operate on 50 μa at 0.25V (12.5 μ w). Figure 19 is the schematic of the unit which is a small 500 kc sine wave oscillator. The test was conducted as follows:

Initially, the sine wave from the oscillator was observed in a cathode tube oscilloscope, using a "C" battery to supply 0.5 V through a potentiometer. A 200g rat was anesthetized with Nembutal and the electrodes (HSS and PPb) were implanted subcutaneously and in the abdominal cavity, respectively. Leads from the rat were then connected to the oscilloscope, at the same time removing the "C" battery from the circuit. The resultant sine wave amplitude was slightly smaller and is shown on the oscilloscope. The voltage measured from the cathode ray tube was between 0.35 and 0.40. (See Figure 1)

A receiver equipped with a loudspeaker was set up on the other side of the laboratory, a distance of about 25 feet. A clear signal was heard when the receiver was tuned to 500 kc. Disconnecting one lead from the rat interrupted the signal for the time that the circuit was broken. Reconnecting the lead permitted the signal to be heard. The output from the oscillator was monitored for 8 hours and visually (oscilloscope trace) resulted in stable transmission.

As the result of the success obtained in powering a specially designed oscillator with the bioelectric potentials, polarization data were accumulated and submitted to the electronic circuitry design personnel in order that small transmitters oscillating in the megacycle range be designed and constructed. A total of six units were received as follows: two crystal controlled, one modulated circuit, the remainder free-running. Schematics for these circuits is shown on Figure 20. Figure 21 shows the relative size of the modulated and free-running transmitters after potting in RTV silicone rubber. These transmitters require an input of 0.17 volts to oscillate. The modulated unit requires 0.23V.

In planning the experiments with the transmitters it was intended to "pot" the devices prior to implantation in dogs. However, a problem with the potting. RTV silicone rubber, the initial choice (See Figure 21) would not adhere to the electrode junctions. Thus, electric shorts and subsequent failure became apparent after a short time. As a result, no long-term transmitter experiments were conducted with these units.

However, externally used, the modulated transmitter performed well. An eight-hour experiment was successfully concluded. A surgical needle was used to pierce the skin in the sternum region of a rat, over the heart, and a hard wire lead was connected between the needle and the proper connection on the transmitter. In this manner a loud, clear heart-beat audible signal was recieved by a commerical band radio reciever at a wave length of 4.8 mc. Since this transmitter was not crystal controlled, the signal was subject to variation in the power inputs. Thus hunting was required to continuously monitor the heart beat. However, by properly designing the transmitter (crystal control) and using the optimum techique for implantation of the electrodes (See Figures 17 and 18), it appears realistic to conclude that a steady state output can be achieved.

V. CONCLUSIONS

The experiments conducted to date have firmly established the feasibility of the utilization of the bioelectric potentials as a primary energy source.

Several combinations of materials have proven to be benign with respect to interacting with the tissues found within the host animal. Of these it is concluded that the optimum electrode system is one composed of an electrode made of high speed steel and the other platinum-platinum black. This system has demonstrated its capability of operating under a 10K Ω load in an unrestrained animal at an output of 0.49 ± .01 V for 128 days.

Should a higher output be desirable, conclusive studies have demonstrated that increasing the area of the PPb electrode results in an increased output.

It is further concluded that the peritoneum cavity appears to be the optimum anatomical locus wherein the electrodes are placed on either side of the pertoneal membrane with the PPb dorsad and the HSS ventrad.

Based on preliminary exploratory-type studies, it is further concluded that this system of implanted electrodes has the capability of powering specially designed transmitters having a modulated circuit such that a physiological parameter, i.e. heart beat, may be transmitted directly form the implanted animal to a radio receiver properly tuned to the transmitter frequency.

VI. RECOMMENDATIONS FOR FUTURE STUDIES

As the result of the many implantation experiments conducted on this contract, it is recommended that additional studies be conducted toward defining the application of the bioelectric potentials. This appears desirable since it is apparent that this source of energy could conceivably act as an important factor in reducing size and complexity of several battery-operated systems which are presently used for monitoring or otherwise studying physiological and psychological responses.

In general, it may be inferred that the usefulness of any electronic device that is capable of sensing, transmitting, stimulating, or measuring any parameter useful in the study of living organisms would be enhanced if a power source could be found which theoretically has a life as long as the life of the living organism. Enumerated below are six general areas which encompass an extremely broad range of disciplines and could conceivably make use of the bioelectric potentials when used in conjunction with properly designed electronic circuitry. It is important to note that the bioelectric potentials and their utilization are suggested here merely as an important research tool and not as a solution to each of the problems that may arise in the various disciplines, i.e. physiology, psycnology, endocrinology, wild life studies, et al.

1. Tracer implants
2. Myo/neuro-electric stimulators
3. Monitoring physiological functions
4. Studying circadian rhythms
5. Study of the electric field stimulation on internal secretory tissues
6. Study the effects of electric field stimulators on growth phenomenon

Area No. 1, implants, includes that broad study area involving tagging and identification studies conducted to investigate wild life.

Here a simple oscillator having a long life would be of great value. Myo-neurological stimulators include such tools as the cardiac pacemaker, diaphragm and sphincter stimulators, and other techniques which may prove useful in aiding a damaged neural or motor function to operate in a more normal manner. Monitoring physiological functions by means of a long-term implanted transducer offers an exciting tool to the physiologist, psychologist, and the medical specialist concerned with the life sciences on earth and space as epitomized by the experiments in which primates will be flown in orbit for extended time periods. In addition, ground based controlled laboratory studies may also be enhanced by virtue of the implanted sensors since the experimental animal will, after recovery from the simple surgical procedure, be unimpaired and completely free of encumbrances, i.e. battery packs, wires penetrating the skin, etc. By this means, it may be possible to determine the effect of stimuli upon various metabolic/physiological outputs in vivo during long-term experiments lasting perhaps years. Area No. 4, Circadian rhythms is basically an application of No. 3. Areas Nos. 5 and 6 are more properly in basic re-search area and involve a means for studying the effects of a continuous mild electrical field stimulation upon hormonal secretions and tissue growth.

Another possible area of application is in clinical medicine. It may be of value to have an implanted sensor which may serve a diagnostic purpose. For example, preliminary experiments suggest that the open circuit voltage may be related to the depth of anesthesia. The respiratory gas composition also has an effect on OCV as measured by a pair of implanted electrodes in a rat.

Considering the state-of-the-art as regards the utilization of the bio-electric potentials, it would appear that the most productive follow-on studies relating to the application of this source of electric power would be in those areas concerned with tracer implants, physiological functions, and circadian rhythms (1, 3, 4). These areas are recommended primarily because:

a) they encompass work that has already been started during the basic studies

b) they will continue the enmassing of data and hence, serve as a source for validating the reasonably long-term experiments that have been conducted during the past year

c) they possess the probability of resulting in electronic circuitry and psychological and physiological data which will have immediate application to the National Space effort

VII. ACKNOWLEDGEMENT

The author wishes to acknowledge the important and vital role played by Mr. L.W. Reynolds who left the General Electric Company prior to the completion of the program. To Mr. F. Cosmi goes our deep appreciation for his devoted attention to detail and his invaluable technical contribution.

VIII. REFERENCES

(1) NASA Contract No. NAS2-1420 dated 17 May 1962 including portions of GE SSL proposal No. N-10092

(2) Pinneo, L.R. and Kesselman, M. L., " Tapping the Electric Power of the Nervous System for Biological Telemetering". ASTIA Document AD 209 067, May 1959.

(3) Long, F. M., "Biological Energy as a Power Source for a Physiological Telemetering System", IRE Intl. Convention Rec., Pt. 9, 1962.

(4) Konikoff, J. J. and Reynolds, R. W., "Results of Some Experiments in Biochemical Electricity." Proceedings of Biochemical Fuel Cell Sessions, Interagency Advanced Power Group, Electrochemical Working Group, Publication PIC - BAT 209/5, Nov. 1962

(5) Reynolds, L. W., "Utilization of Bioelectricity as Power Supply for Implanted Electronic Devices," Aerospace Med., 35, 115, Feb. 1964.

XI. BIBLIOGRAPHY

(1) Quarterly Reports for November 1963, Feburary 1964

(2) Interim Report - September 1963

(3) Monthly Reports for January, March, April 1964

All Concerned With The Subject Contract - NASA/ARC Contract NAS2-1420

TABLE I

Part 1

Output as a Function of Electrode Material

Electrode Material Subcutaneous	Abdominal	OCV	Output under Load Resistance Ohms	V	μa	μw
White gold	PPb	.35	10K	.03	3.0	0.09
Molybdenum	PPb	.40	10K	.25	25.0	6.25
Bone plate	PPb	.35	10K	.22	22.0	4.84
Lead	PPb	.74	10K	.42	42.0	17.6
Antimony	PPb	.65	10K	.40	40.0	16.0
Brass	PPb	.46	10K	.23	23.0	5.25
Silver amal.	PPb	> 1.00	10K	.43	43.0	18.5
Silver	PPb	.25	1K	.06	60.0	3.6
Inconel	PPb	.33	1K	.08	80.0	6.4
Platinite	PPb	.45	1K	.08	80.0	6.4
Titanium	PPb	.27	10K	.06	6.0	0.36
Hafnium	PPb	< .35	Erratic - dropping potential			
Silver/lead amal	PPb	.83	10K	.32	32.0	10.24
Lead amal	PPb	.69	10K	.37	37.0	13.69
Hi-speed steel	PPb	.69	10K	.54	54.0	29.2
Carbon	PPb	.28	10K	.23	23.0	5
Mu-metal	PPb		1K	.33	330	110

TABLE I

Part 2

Output as a Function of Electrode Material

Electrode Material Subcutaneous	Abdominal	OCV	Resistance Ohms	Output under Load V	μa	μw
Cr	Ag-amal	.40	10K	.21	21.0	4.41
Ag-amal	Cr	.30	10K	.15	15.0	2.25
Sb	Ag-amal	.34	10K	.17	17.0	2.89
Hf	Ag-amal	.43	10K	.05	5.0	0.25
Ag-amal	Hf	.40	10K	.06	6.0	0.36
Hf	None	.12	10K	-	-	-
None	Hf	.20	10K	-	-	-
Hf-Ag amal	None	.47	10K	.06	6.0	0.36
Pt-10% Rh	PPb	.30	2.4K	.12	50	6.0
Pt	PPb	.12	.5K	.01	20	.2
Pt - 10% Rh	PPB-DECO	.25	20K	.22	11	2.4
Pt	PPb-DECO	.06	20K	.02	1	.02
Pt	Pt-10% Rh	.10	4K	.01	2.5	.025

Part 3

Output as a Function of Electrode Material

Electrode Material Subcutaneous	Abdominal	OCV	Resistance Ohms	Output under Load V	μa	μw
Manganese steel	PPb		.5K	.34	680	231
Monel	PPb		5K	.28	56	15.7
Platinite	PPb		1K	.08	80	6.5
Brom.Hi-T alloy	PPb		1K	.07	70	4.9
Ag	PPb		1K	.06	60	3.6
PPb	Ta	.44	10K	.13	13	1.7
Ta	PPb	.42	10K	.34	34	11.6
SS 310	PPb	.26	1K	.07	65	4.2
Hastaloy	PPb	.39	10K	.10	100	10
Stainless[(a)]	[(b)] PPb-DECO	.68	.5K	.24	480	115
Stainless	PPb-DECO	.74	1K	.22	220	48
Stainless	PPb	.63	1K	.28	280	78
Nickel & Alloy[(c)]	PPb-DECO	.46	1.75K	.30	170	51
Stainless	PPb	.29	10K	.06	6	4
Ni Foam	PPb	.58	1K	.16	155	24
Ni Plate	PPb	.46	1K	.14	140	19.6
Ni Foam	PPb		10K	.27	22	4.8
Ni Plate	PPb		10K	.20	20	4.0
PPb	Ni Plate	.24	1K	.11	110	12

a) Artery clamp
b) G.E. Co., Direct Energy Conversion Operation, Lynn, Mass.
c) Five-cent piece

TABLE II

Material Composition

Electrode Material	Percent Composition									
	Fe	Ni	Cr	Cu	Co	Mn	W	V	Si	C
1. Monel Metal	6.5	60.0	-	33.0	-	-				0.5
2. Manganese Steel	86.0	-	-	-	-	13.0	-	-	-	1.0
3. High-speed steel	75.0	-	6.0	-	-	-	18.0	0.3	-	0.7
4. Platinite	53.85	46.0	-	-	-	-	-	-	-	0.15
5. Bram Hi-Temp. Alloy	53.67	24.6	18.8	-	-	-	-	-	2.5	0.43
6. S.S. Bone Plate	63.67	12.0	18.5	-	-	2.0	(Mo 3-0)		0.75	.08
7. Gold (Pure)	99.99									
8. Silver (Pure)	99.99									

TABLE III a

Power Output Obtained from a Single Anatomical Locus

(Both electrodes subcutaneous)

Electrode Material	OCV	Resistance Ohms	Output under Load V	μ a	μ w
HSS - PPb		10K	.32	32	10.6
Manganese Steel-PPb		10K	.38	38	14.4
Monel - PPb		1K	.10	100	10.0
Ni Foam - PPb	.51	5.6K	.28	60	14.0
PPb - PPb	.06	-	-	-	-
Ag - PPb	.21	2.5K	.10	40	4.0
Hastaloy - PPb	.25	9.5K	.14	15	2.1

TABLE IIIb

Power Output Obtained from a Single Anatomical Locus

(Both electrodes abdominal cavity)

Electrode Material	OCV	Resistance Ohms	Output under Load V	Output under Load μ a	Output under Load μ w
HSS - PPb		10K	.35	35	12.2
Manganese steel - PPb		10K	.40	40	16.0
Monel - PPb		10K	.26	26	6.7
Platinite - PPb		1K	.08	80	6.5
Ag - PPb		1K	.06	60	3.6
Ag - PPb	.22	2.6K	.09	34	3.1
Ni Foam -PPb	.31	2.2K	.11	50	5.5
PPb - PPb	.24	3.8K	.19	50	9.5
Hastaloy - PPb	.30	1.9K	.14		

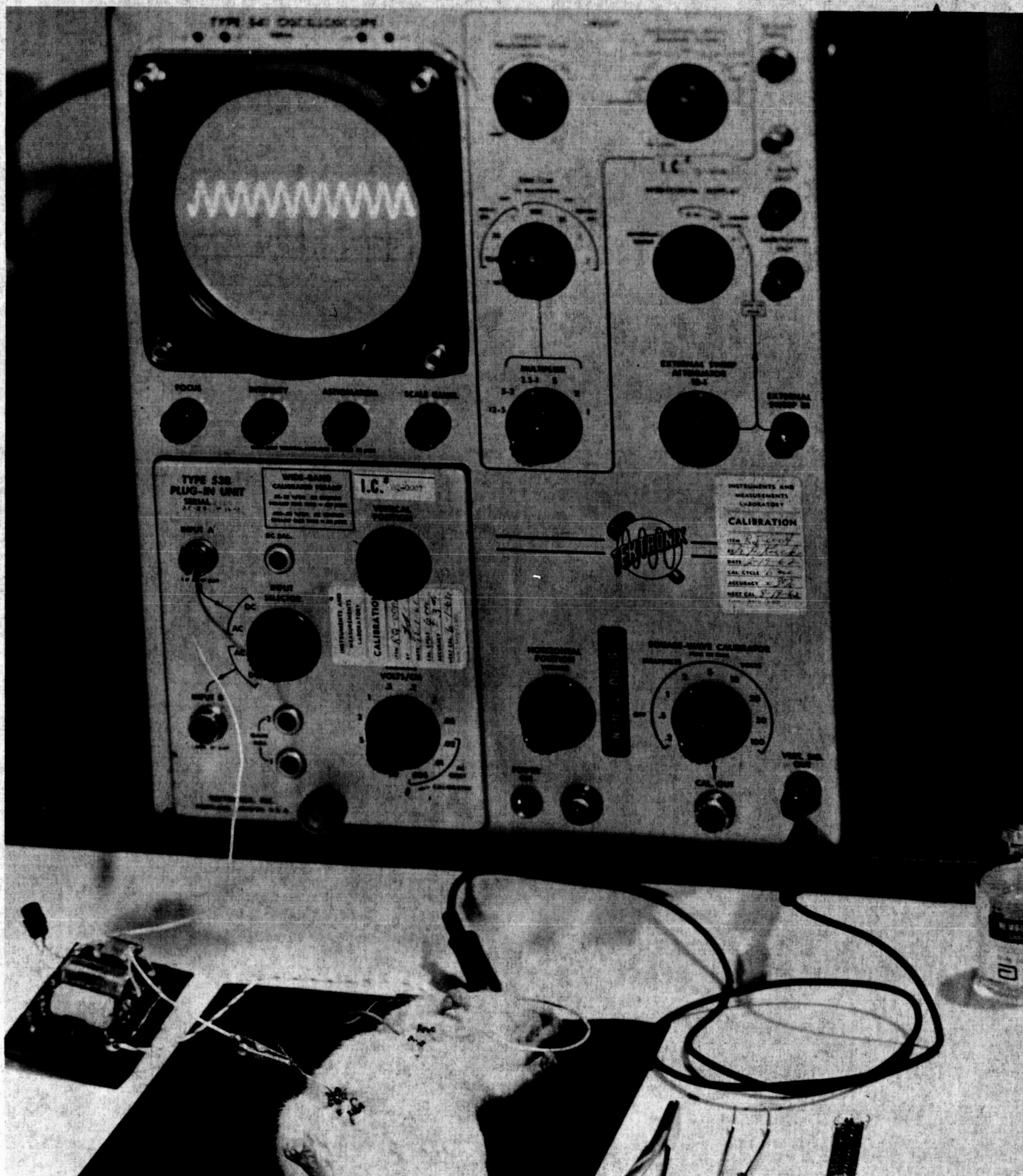


Figure 1. Early Experiment - Rat Powered Oscillator

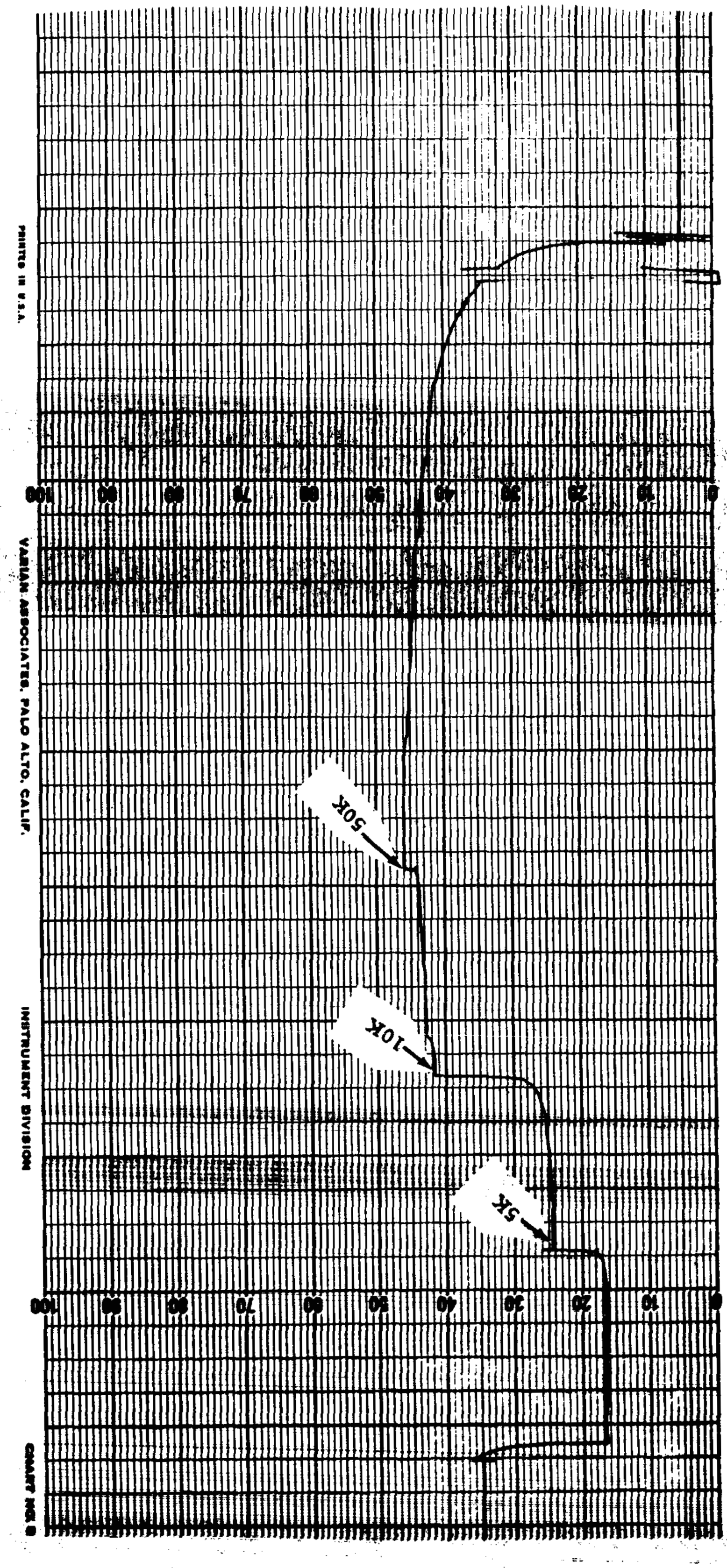


Figure 2. Typical Polarization Curve (Pt/Pt-Black + Cr)

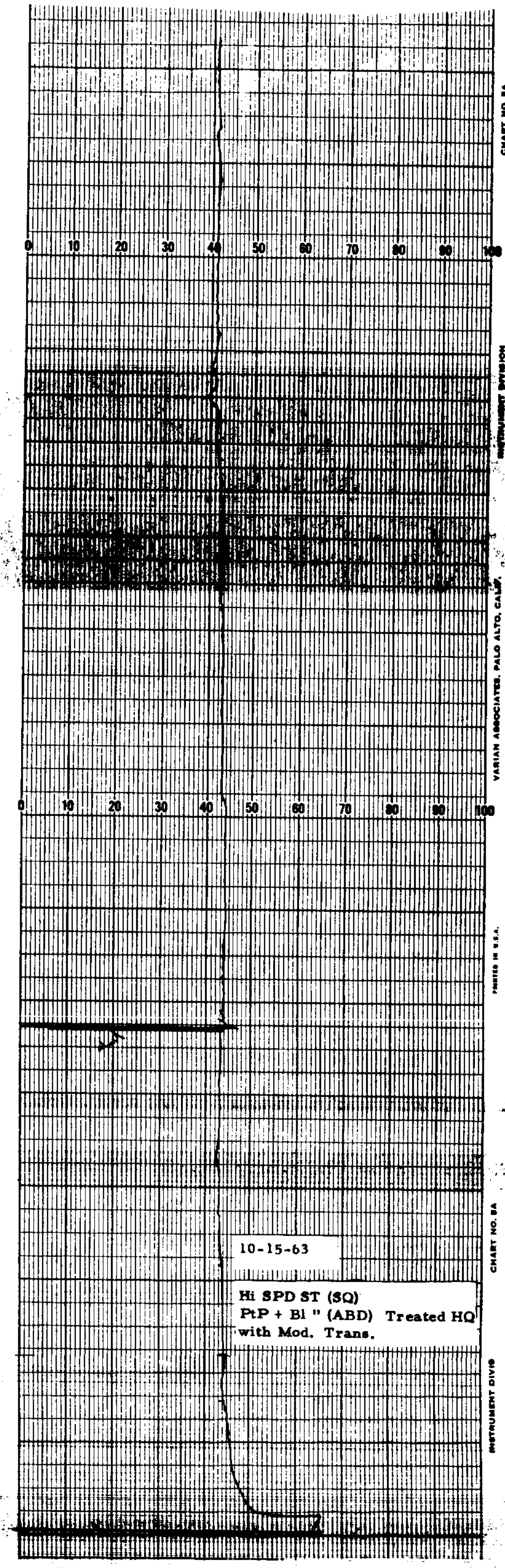


Figure 3. Voltage Drop under 10K Ω Load - Approx. 8 Hrs.

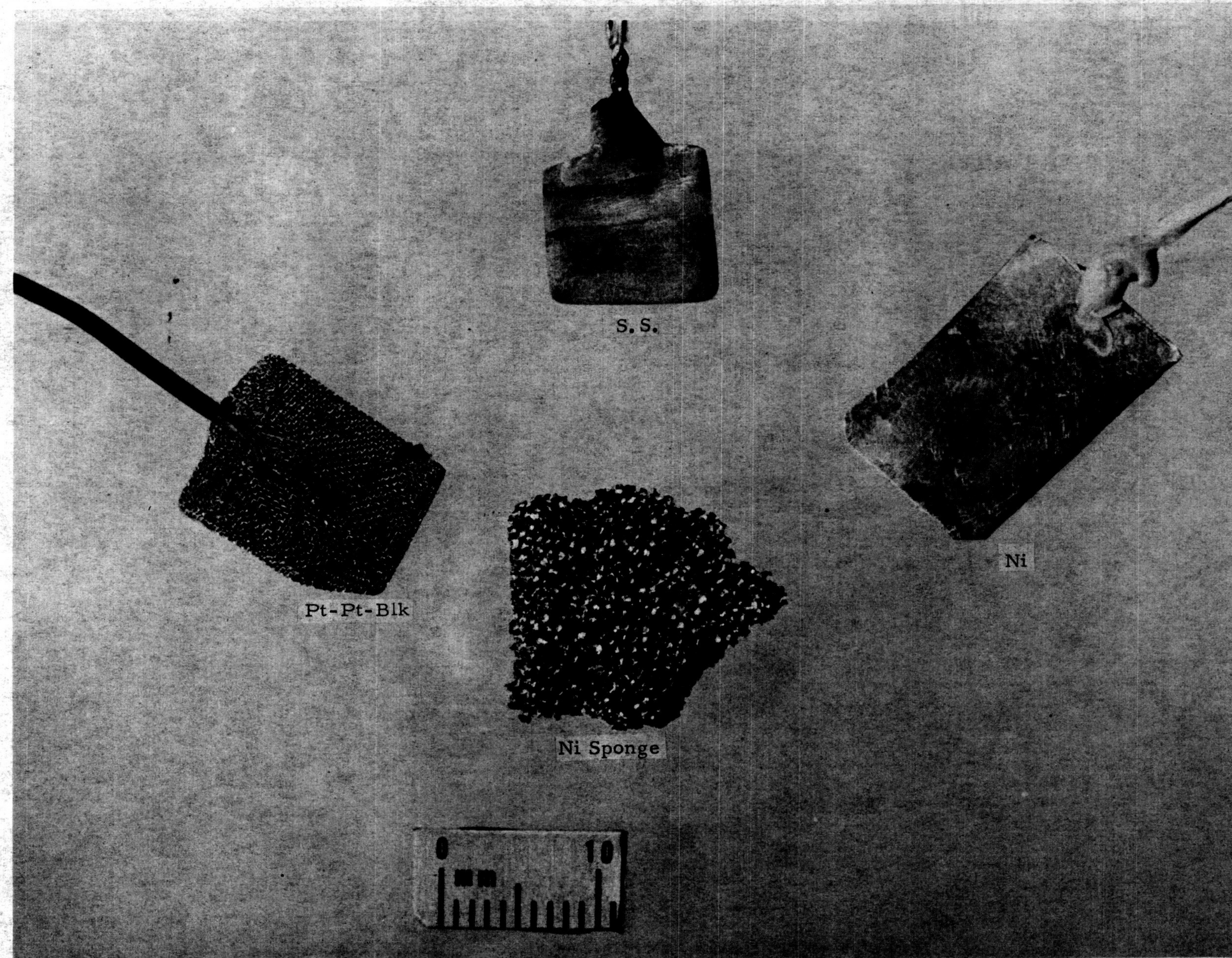


Figure 4. Examples of Electrode Material

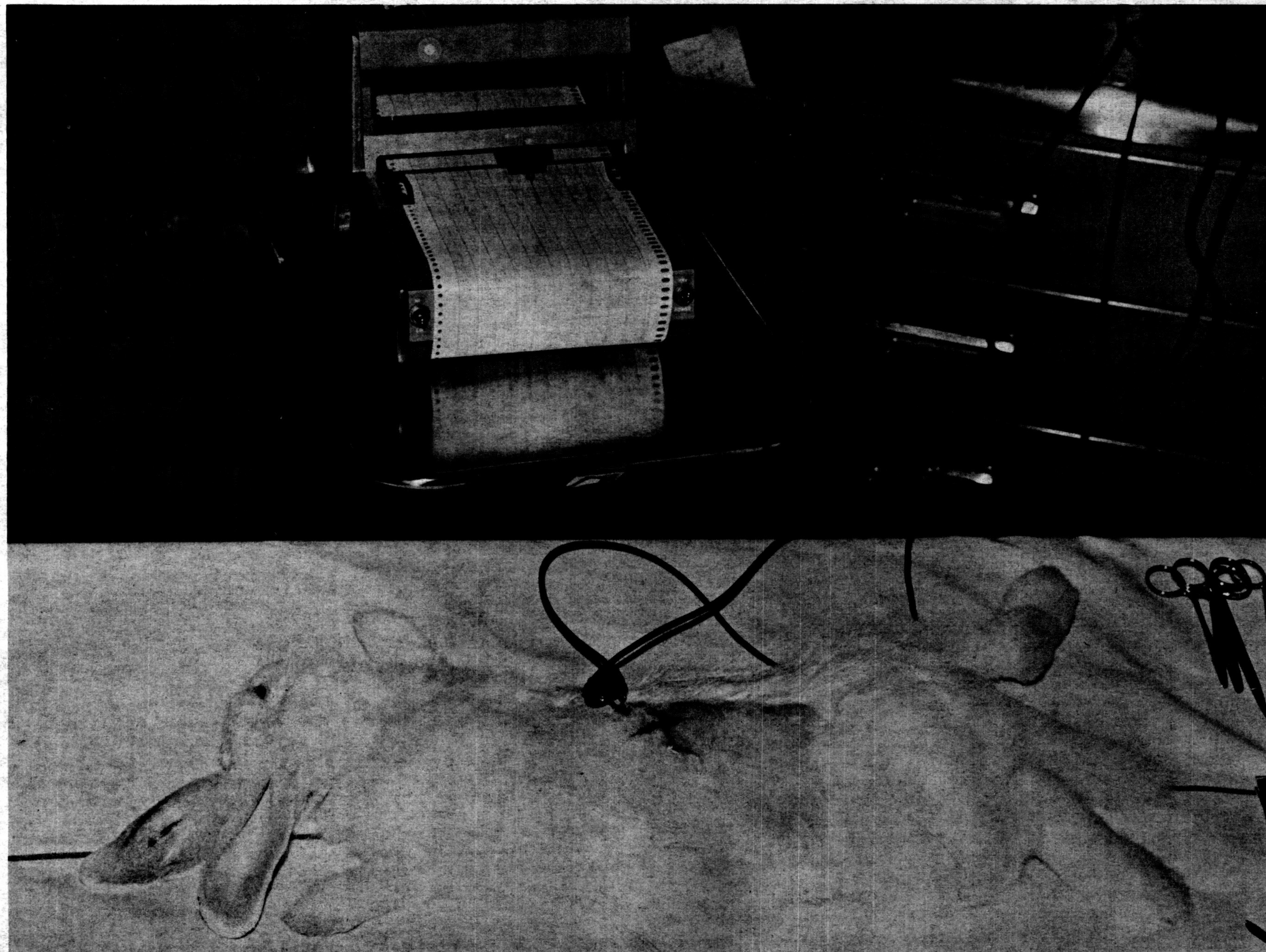


Figure 6. Another View of Rabbit Implantation

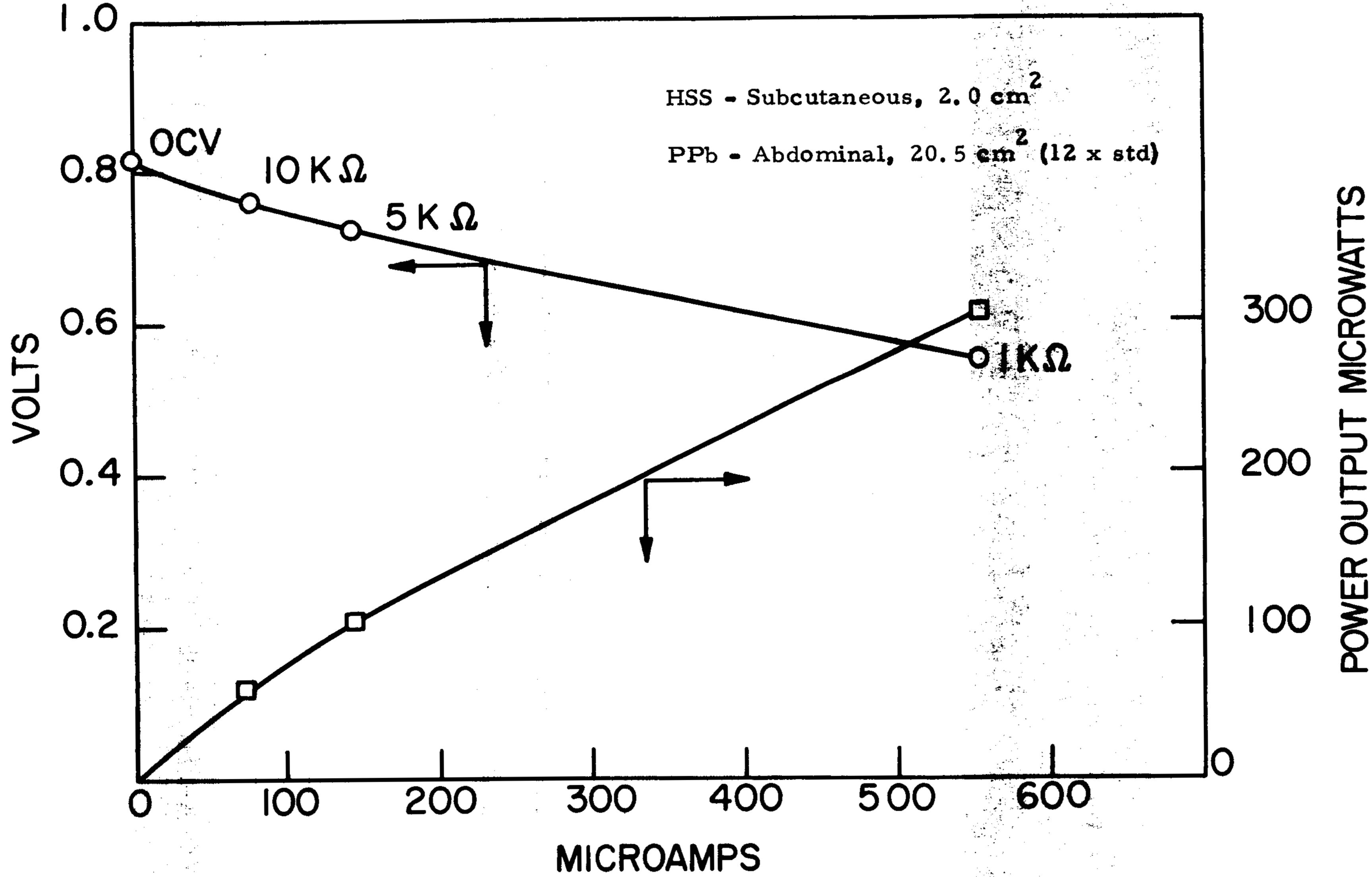


Figure 7. Polarization Curve, Extended Surface Area, PPb Electrode

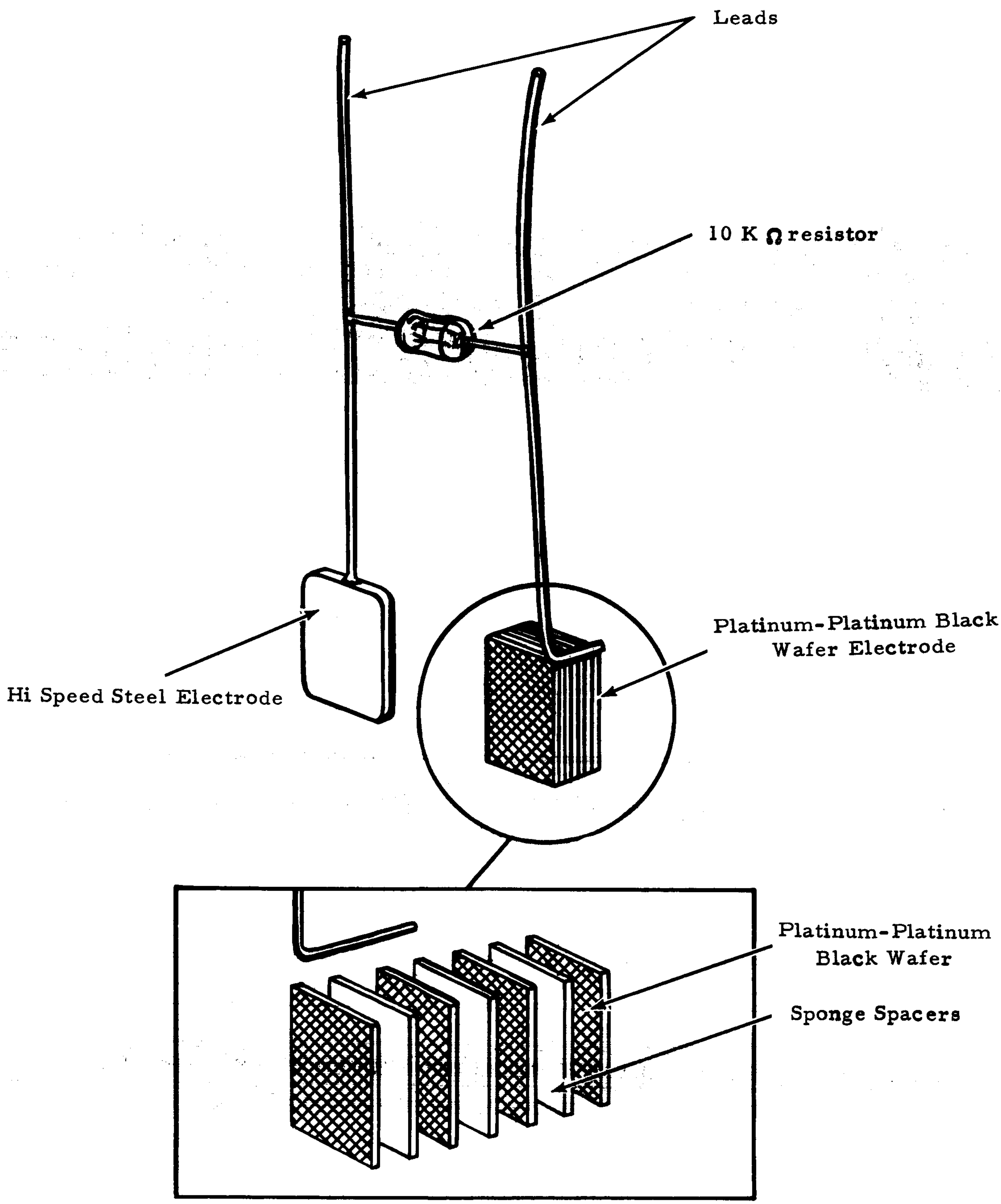


Figure 8. Sketch of Wafer PPb - HSS Circuit

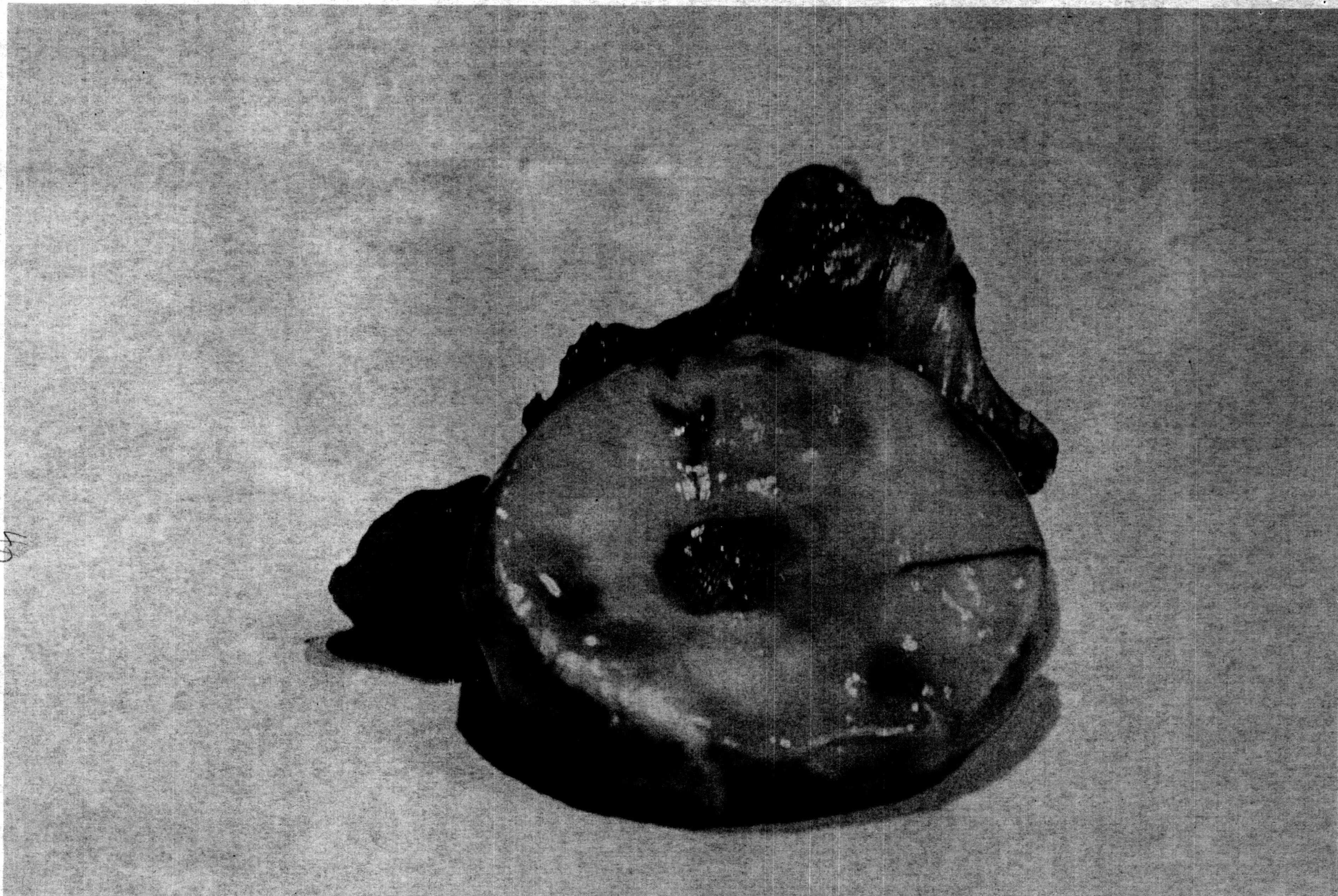


Figure 9. PPb Electrode after 160 Days Implantation in a Rabbit (See Figure 11)

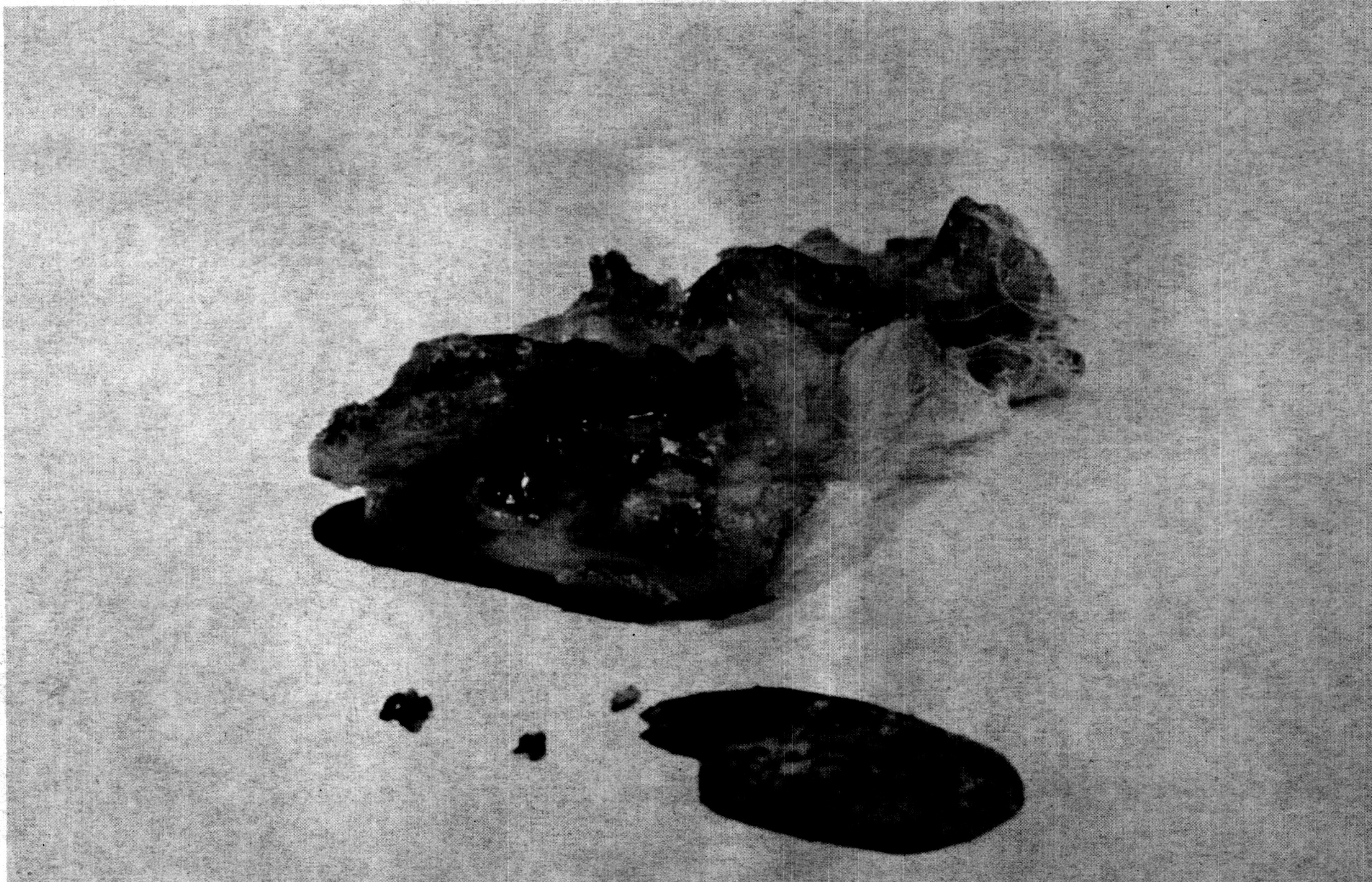


Figure 10. Chromium Electrode after 160 Days Implantation in a Rabbit (See Figure 11)

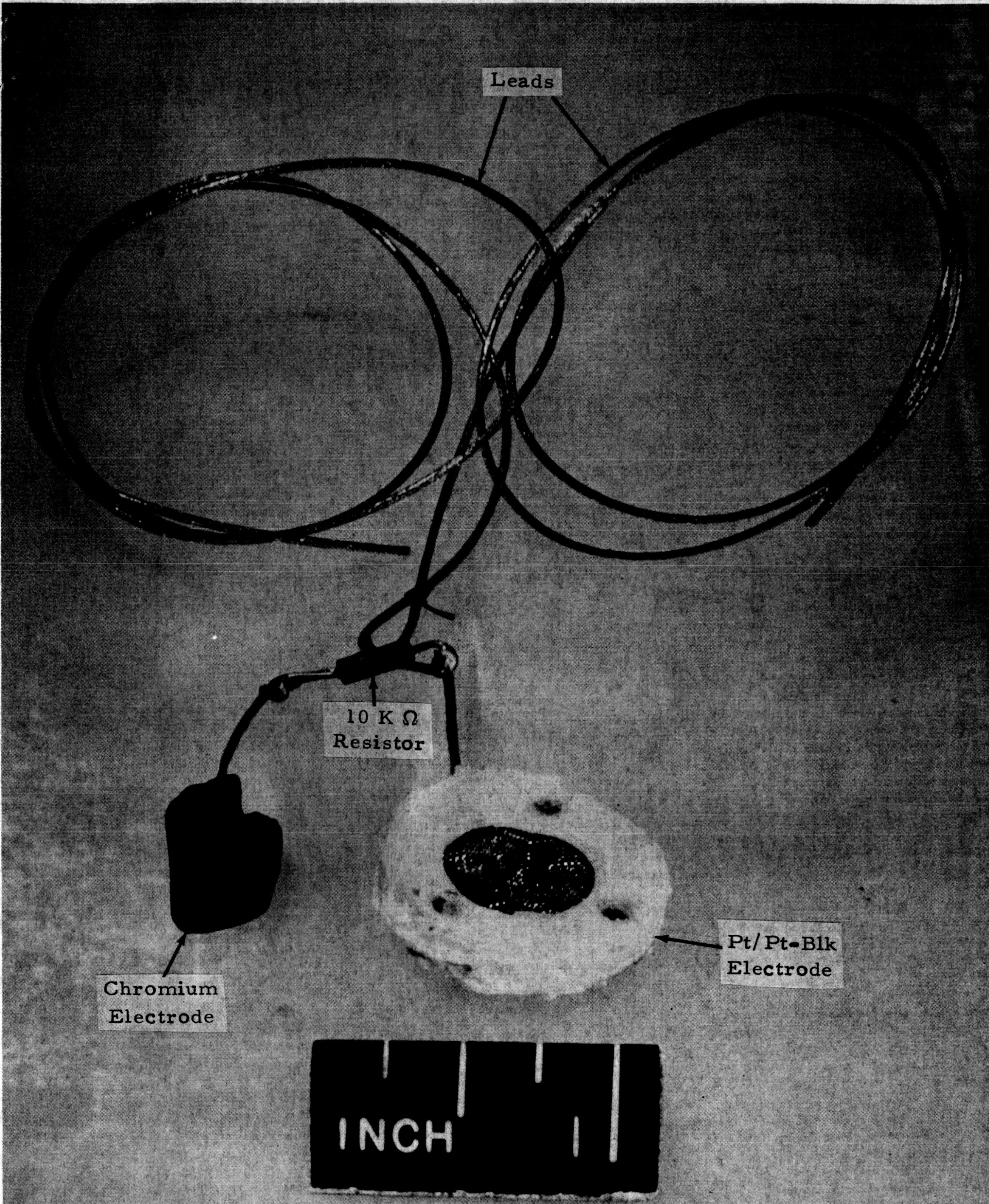


Figure 11. Circuit Used for Long Term Implant (Potted PPb)

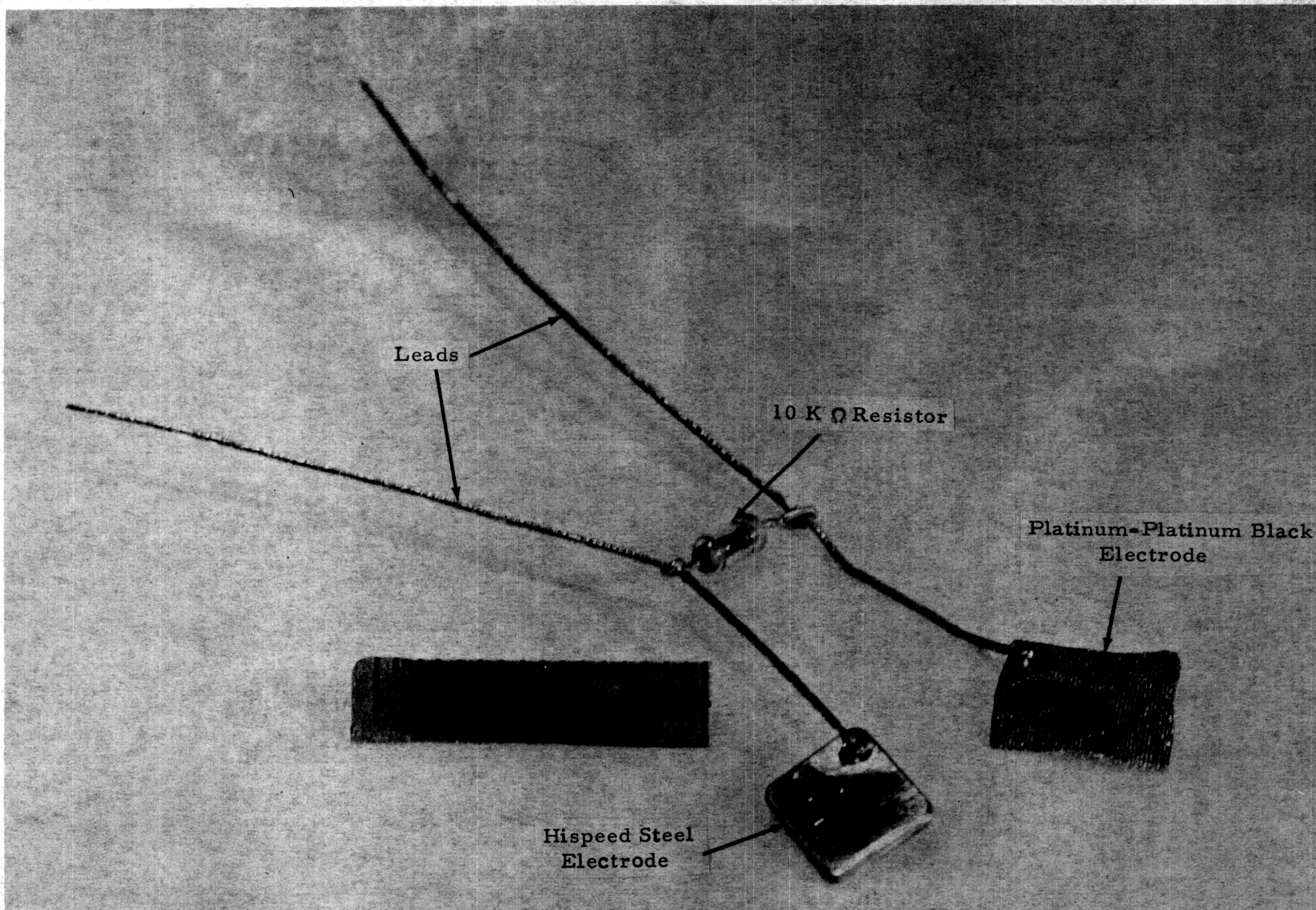


Figure 12. Circuit Used for Long-term Implant (HSS - PPb)

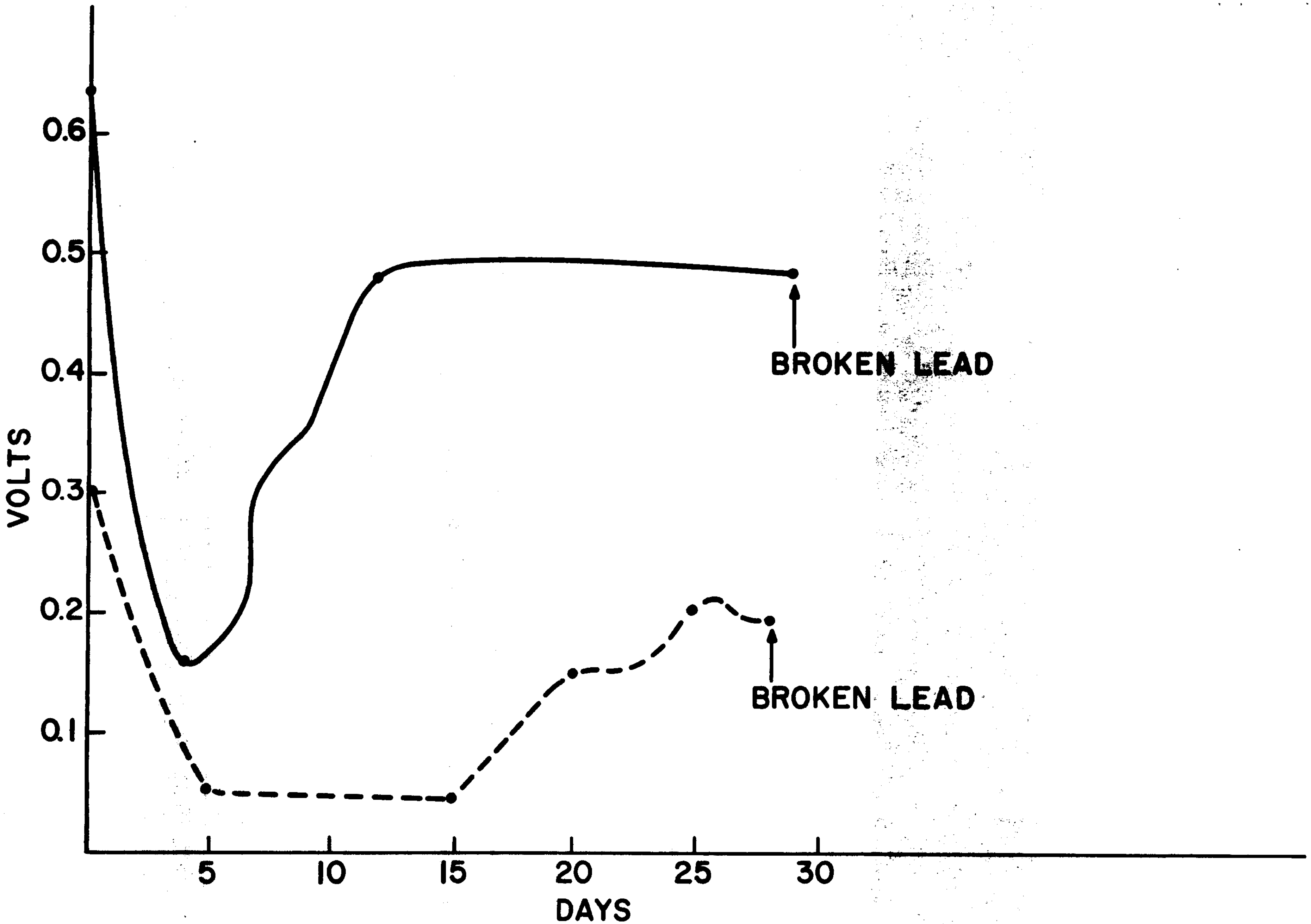


Figure 13. Long Term Implant Study. Animal - Rabbit; Electrodes - (Pt/Pt Blk - Abdominal Cavity, Chromium - Subcutaneous:----(Pt/Pt Blk - Abdominal Cavity, Hi Speed Steel - Subcutaneous): ——— ; Circuit - 10KΩ Resistance in Parallel)

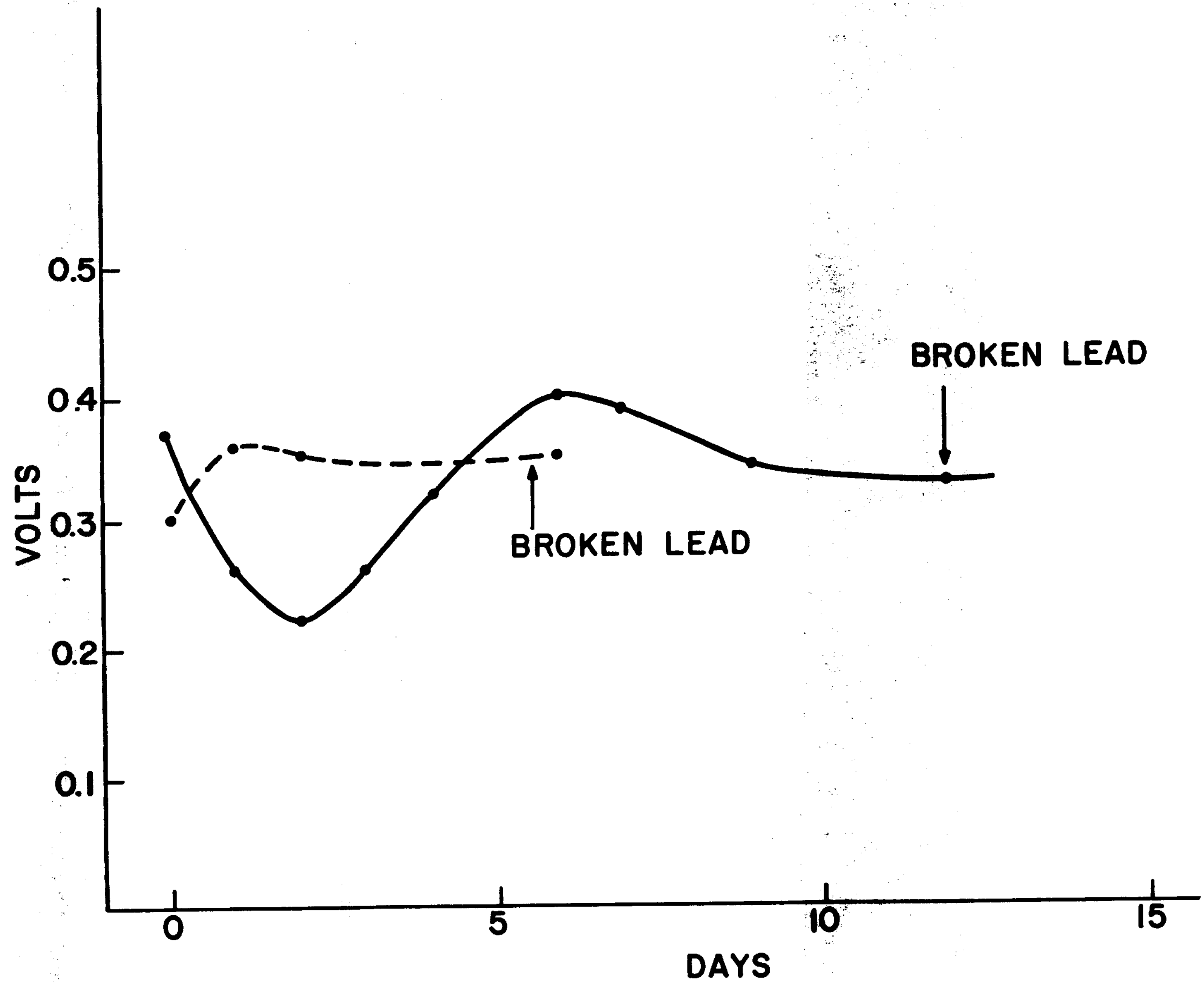


Figure 14. Long Term Implant Study. Animal - Rabbit; Electrodes - **Pt/Pt Blk** - Abdominal Cavity, Chromium - Subcutaneous ----(Pt/Pt Blk - Abdominal **Cavity**, Hi Speed Steel -Subcutaneous) ——; Circuit - 10KΩ Resistance in Parallel

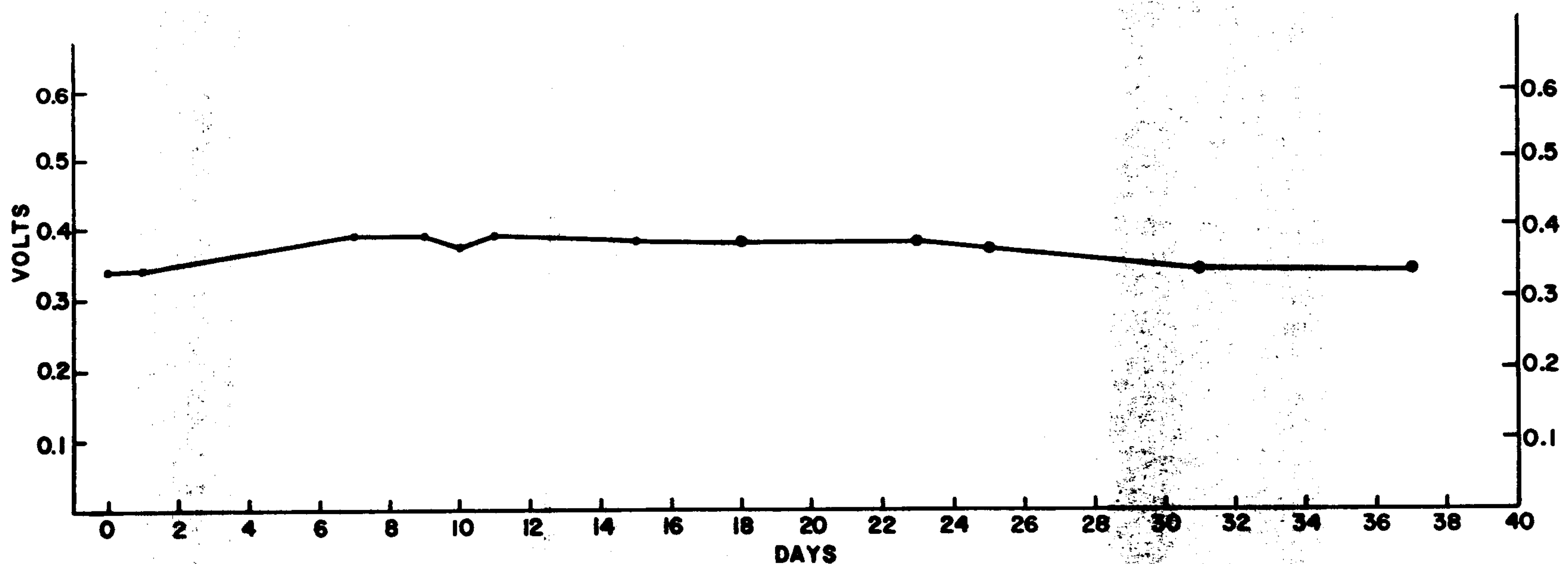


Figure 15. Long Term Implant Study; Animal - Dog; Electrodes - Pt/Pt Blk and Hi Speed Steel Separated By Peritoneal Membrane; Circuit - 10K Ω Resistance in Parallel

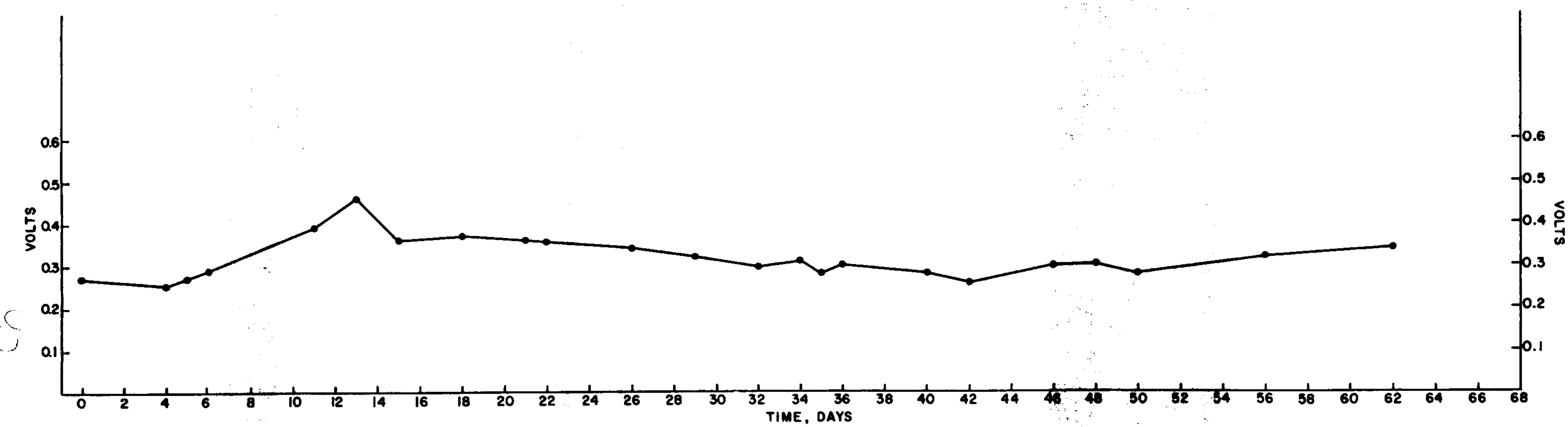
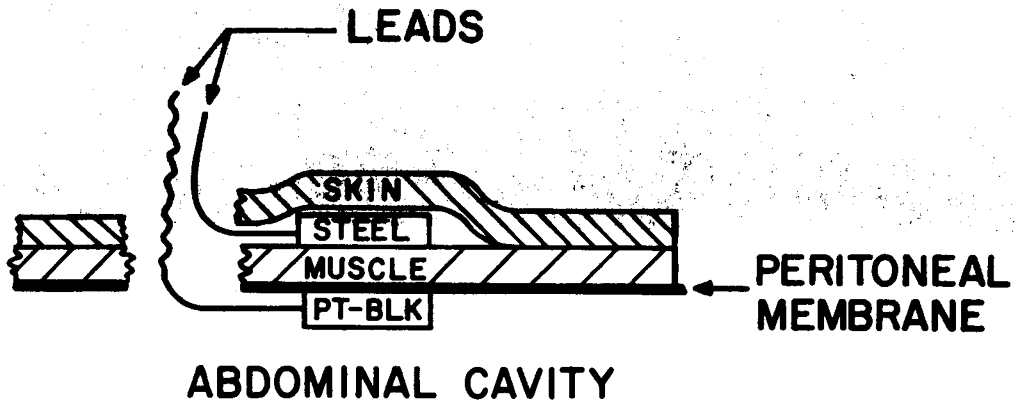
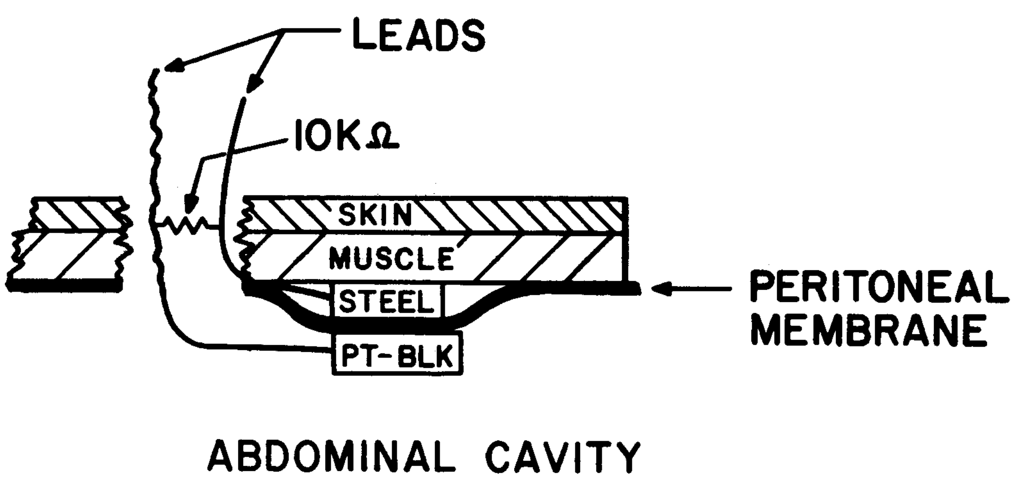


Figure 16. Long Term Implant Study. Animal - Dog; Electrodes - Pt/Pt Blk (Abdominal Cavity) Hi Speed Steel (Subcutaneous) ; Circuit - 10K Ω Resistance in Parallel



a. STANDARD LOCATION OF ELECTRODES



b. ELECTRODES SEPARATED BY PERITONEAL MEMBRANES

Figure 17. Schematic Sketch Showing Electrode Positioning

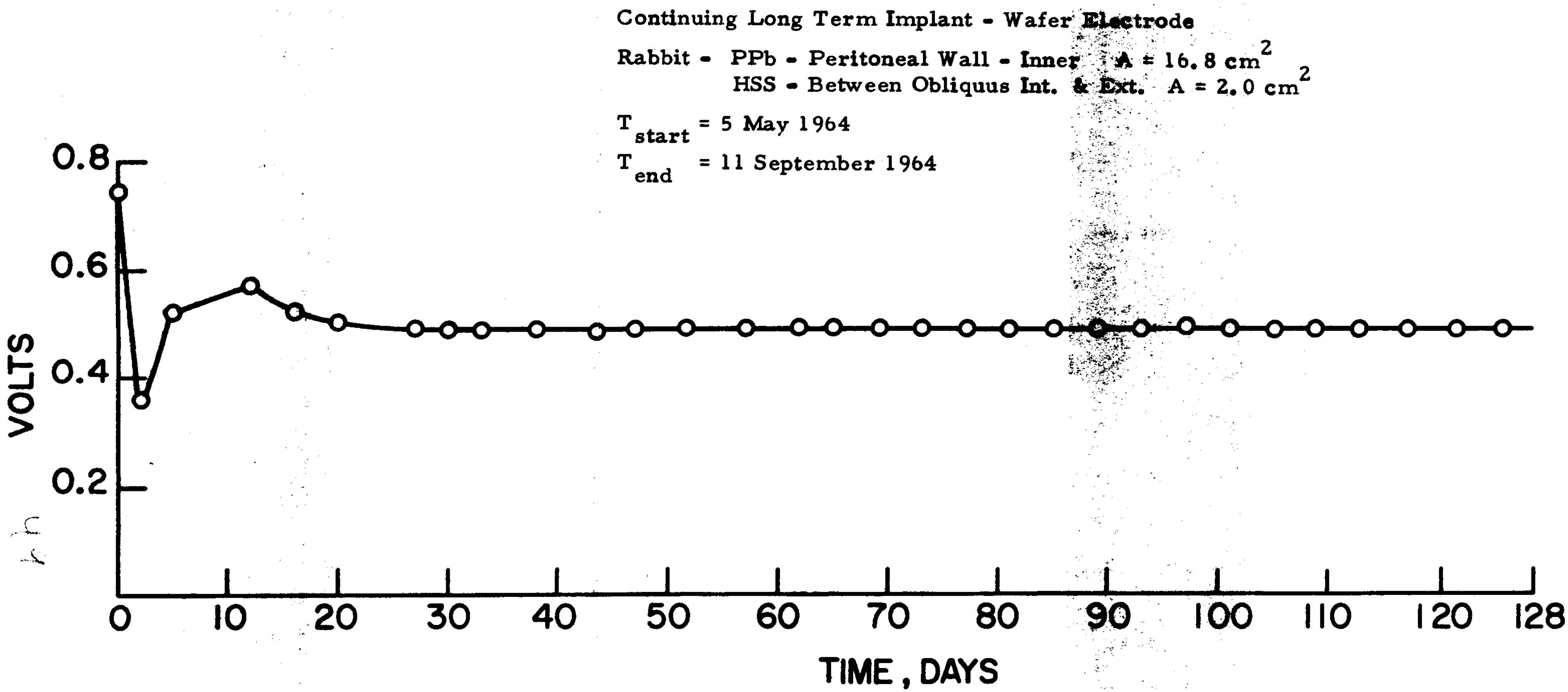


Figure 18. Long-term Implant Study (128 days - Rabbit)

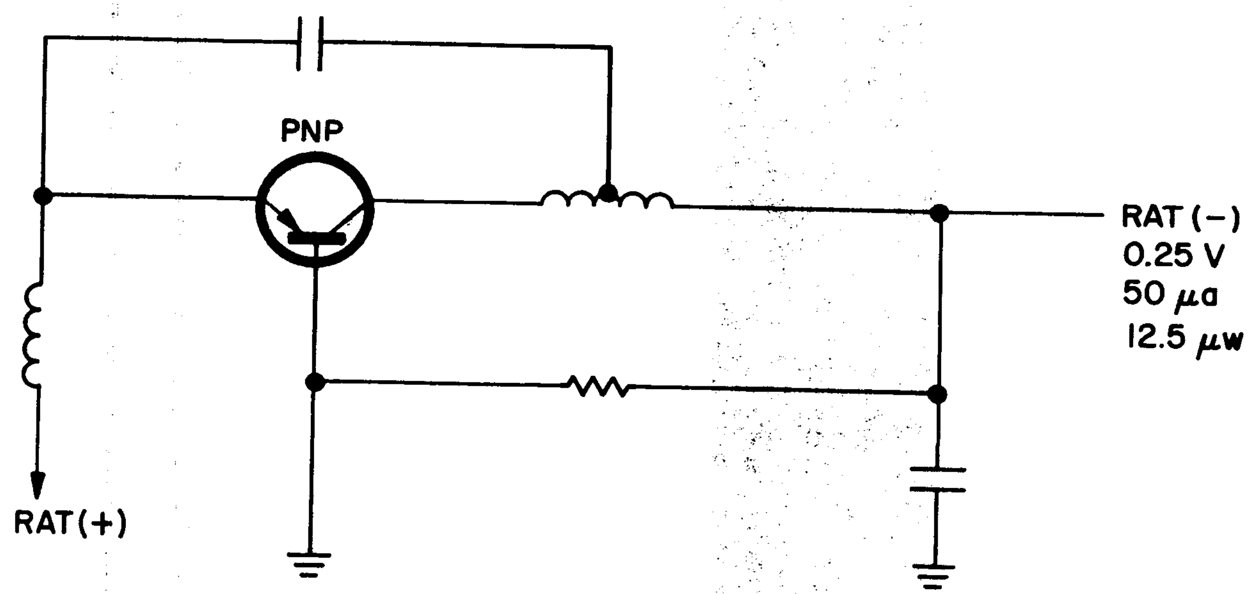
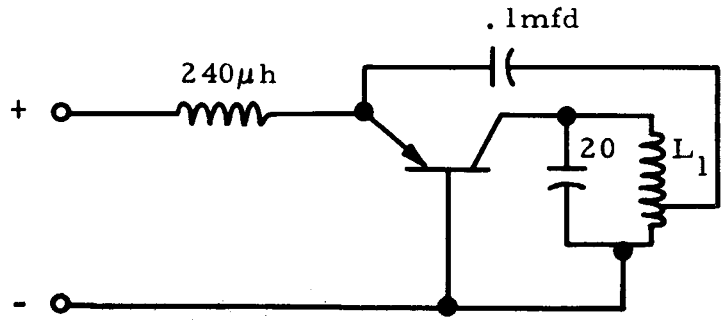


Figure 19. Schematic of 500 kc Oscillator

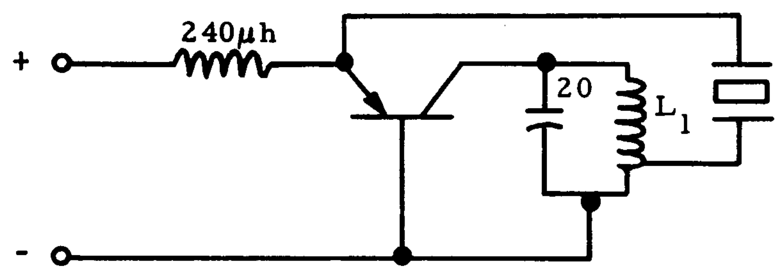
4 MEGACYCLE TRANSMITTER

(a)



4 MEGACYCLE CRYSTAL CONTROLLED

(b)



4 MEGACYCLE TRANSMITTER (MODULATED)

(c)

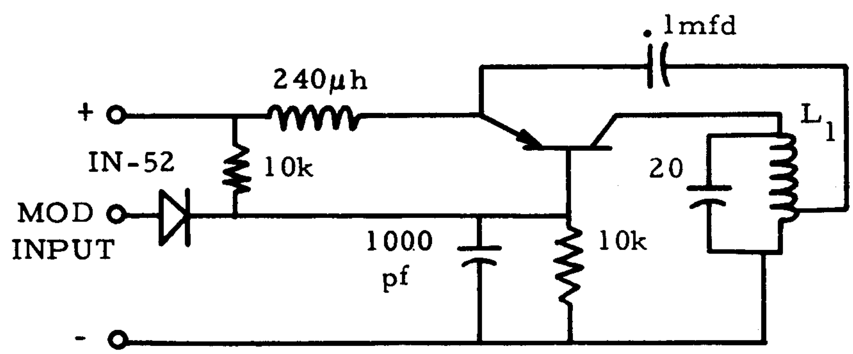


Figure 20. Schematic of Three Special Transmitters

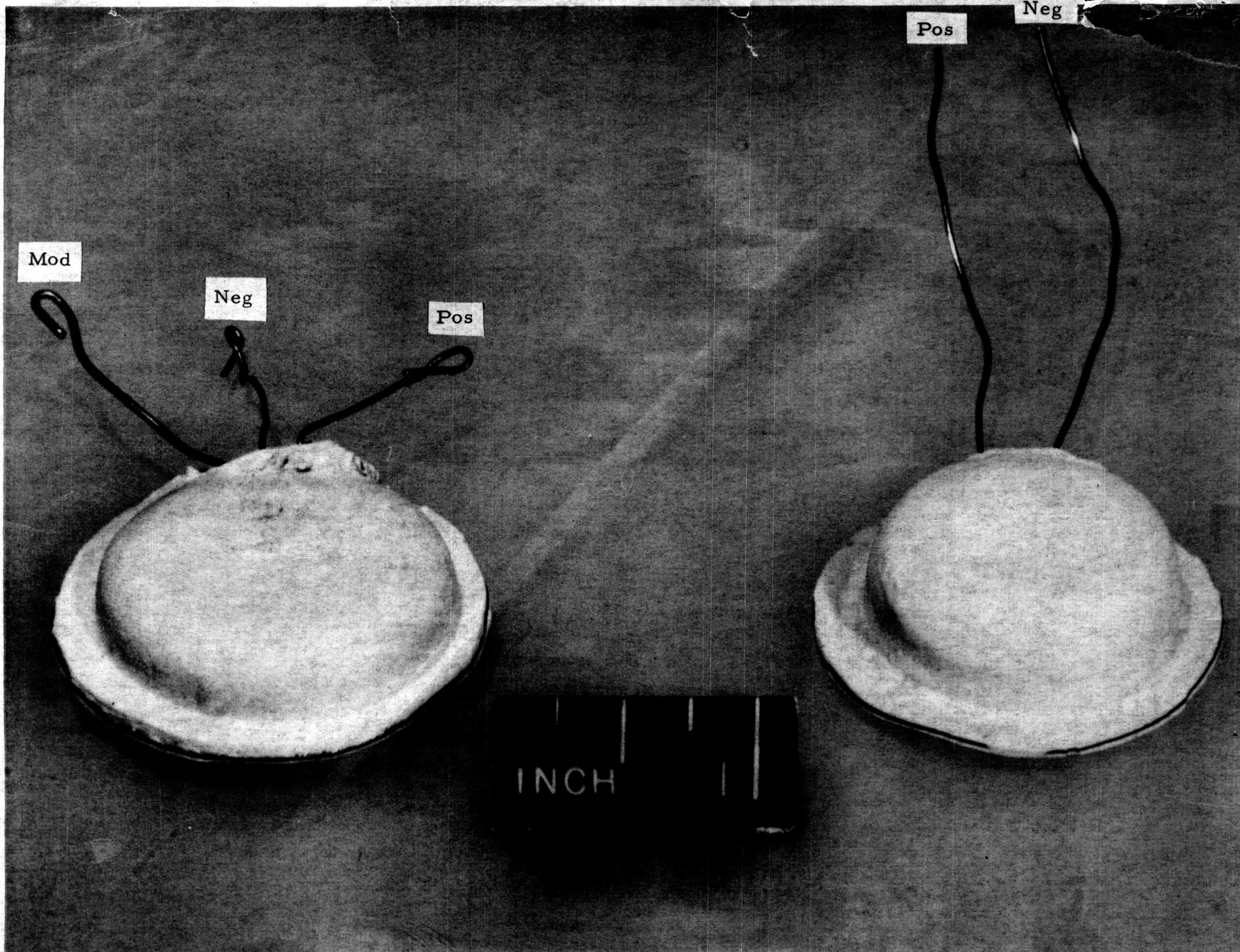


Figure 21. Modulated and Non-modulated Transmitters